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The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis

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HIGHLIGHTS

- A multi-objective search to minimise the building total energy need was performed.
- Number, position, shape and type of windows and the thickness of walls were varied.
- The analyses were performed for different climates and urban contexts.
- A post-Pareto analysis was performed through a box plot elaboration.
- A small area was found for non-south facing windows in all locations.

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ABSTRACT

The majority of decisions in the building design process are taken in the early design stage. This delicate phase presents the greatest opportunity to obtain high performance buildings, but pertinent performance information is needed for designers to be able to deal with multidisciplinary and contrasting objectives. In the present work, an integrative approach for the early stages of building design is proposed to obtain detailed information on energy efficient envelope configurations. By means of genetic algorithms, a multi-objective search was performed with the aim of minimising the energy need for heating, cooling and lighting of a case study. The investigation was carried out for an open space office building by varying number, position, shape and type of windows and the thickness of the masonry walls. The search was performed through an implementation of the NSGA-II algorithm, which was made capable of exchanging information with the EnergyPlus building energy simulation tool. The analyses were conducted both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo. In addition, a preliminary analysis on the Pareto front solutions was performed to investigate the statistical variation of the values assumed by the input variables in all the non-dominated solutions. For the analysed case study, results highlighted a small overall Window-to-Wall Ratio (WWR) of the building in all locations. Pareto front solutions were characterised by low WWR values especially in east, west and north exposed façades. The area of the south facing windows was higher compared to the other orientations and characterised by a higher variability.

1. Introduction

The early stage of building design is characterised by multidisciplinary and contrasting objectives. In this phase, designers consider the largest number of design possibilities and have to make the majority of decisions in the entire process. It is traditionally accepted that end cost, energy efficiency and general performance of buildings are strongly determined in the early stages of design [1–3]. As a consequence, this phase presents the greatest opportunity to obtain high performance buildings. However, design decisions influence different aspects of the building which are often in contrast with one another. A good example of these contrasts is natural illumination versus solar shading. Designers therefore need to gather pertinent building performance information to be able to deal with contrasting objectives.

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Nomenclature

E	electric energy (kWh_e/m^2)
Q	thermal energy (kWh_t/m^2)
R	thermal resistance (m^2 K/W)
U	thermal transmittance (W/m^2 K)
c_p	specific heat (J/kg K)
g	solar energy transmittance (–)
t	thickness (m)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
τ_l	visible transmittance (–)

Subscripts

C	cooling
H	heating
L	lighting
e	east
g	glazing
n	north
nd	need
s	south
w	west

The building envelope is perhaps one of the most interesting subjects with regard to multidisciplinary design. Envelopes have a major role in the building's exposure to the elements; they have a great impact on energy efficiency and indoor environmental quality. Envelopes are also an important component in the building structure and are a big part of their budget.

Several articles detailing the use of various search, optimisation and design support algorithms in the building and construction industry have been published. A great variety of performance objectives can be addressed and many design variables can be optimised to reach the intended goals. Energy demand, system loads, construction and operating cost, thermal comfort, life cycle cost, life cycle environmental impact and CO_2 emissions are among the most investigated objectives in the building sector. Even though the majority of studies focused on building design, optimisation approaches are not limited to new constructions. They were also applied to optimise envelope and systems for refurbishing existing buildings [4–6].

Attia et al. presented a full review of current Building Performance Optimisation (BPO) tools for net zero energy building design [7]. Nguyen et al. [8] and Evins [9] reviewed simulation-based optimisation methods applied to building performance analysis and sustainable building design problems. Optimisation of passive solar design strategies were reviewed by Stevanović [10], who provided a summary with regard to building form, opaque envelope components, glazing and shading elements and whole building passive solar design optimisation. Machairas et al. presented a review on algorithms for optimisation of building design [11].

Search algorithms in combination with parametric models and dynamic energy simulation software were employed to determine optimal configurations of several building components including the building envelope. A literature review of building envelope design can be found in [12]. Some authors optimised the thermo-physical properties [13,14] or insulation thickness [15–19] of the opaque envelope. Other researches studied optimal Window-to-Wall Ratio (WWR) configurations [20,21] or combined an optimisation of thermo-physical properties and WWR [12,22–25]. Several researches focused on the optimisation of shading devices [26,27] or the combination of shading device and window area [28]. Building operation [29] and optimal scheduling strategies [30] were also investigated. An optimisation of both envelope and HVAC systems was performed in [23]. Even though a combined optimisation of envelope and HVAC systems was found to be preferable to a sequential approach where the HVAC systems are optimised after the envelope, only slightly better results were obtained at the expense of a considerable increase of the computational run time.

Size, number and position of windows were optimised for a south facing façade in terms of energy efficiency by means of a genetic algorithm in [20]. Building shape was investigated as part of the envelope optimisation in [31]. Building layout and shape for the initial design stage of a building with given envelope properties were respectively optimised in [32] and [2,33]. Curtain wall façade components were studied in terms of carbon emissions during the entire building operation in [34]. Glare and illuminance of several fenestration configurations were studied and optimised in [35]. A sensitivity analysis of the WWR was also studied in [36].

The present work proposes the use of Multi-Objective Genetic Algorithms (MOGAs) in the early stages of design of an office building. An integrative approach which involves the simultaneous optimisation of the façades is presented for the design of the building envelope. The building energy need for heating, cooling and lighting were chosen as objective functions. The analyses were conducted both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo.

Parametric models were used to represent envelopes for the optimisation of number and type of windows, as well as their size, shape and position in each façade. The variation of window shape and position ensured that not only the WWR was studied, but also height to length ratios of the windows and their position along the building façades. In addition, the parametric models that were adopted could modify the thickness of the masonry walls to provide shading to the windows while keeping a fixed U-value.

Most of the existing research articles dealing with WWR analyses proposed a façade optimisation which was independent for each orientation. This approach is limited when it comes to the design of an entire building floor, because it is unlikely that the combination of optimised north, south, east and west orientations will produce an optimal result overall. Combining optimal window arrangements resulting from separate search processes is an approach that does not take the interaction of these windows in the same space into account. Moreover, searching for the optimal WWR is limited when the windows are set back from the outer edge of the walls and when the optimisation of the energy need for lighting is also involved. Even though the WWR has a major role in the energy efficiency of buildings [37], solar gains are not independent from the window shape when reveals provide shading to the windows [38]. In addition, the position of windows has an influence on the daylighting.

In the present work, the use of multiple fitness functions in a multi-objective optimisation is proposed as an HVAC-indepen dent search process. The use of multi-objective search algorithms has an important advantage from a design point of view. The data that is gathered during the process contains detailed information regarding the heating, cooling and lighting needs of each proposed solution. Even though aspects such as aesthetics or visibility towards the outside were not introduced as explicit search variables, they can nevertheless be considered in the final selection of a solution to pursue.

Suga et al. [39] presented a post-Pareto analysis aimed at classifying the optimal solutions in relation with their performance in the selected objective functions. In this paper, a statistical analysis to retrieve information on the design variables which lead to optimal solutions was performed. This kind of investigation can potentially provide highly relevant information for the early stage of the design process.

2. Methods

This article presents the use of Multi-Objective Genetic Algorithms in combination with parametric models and energy simulation software to obtain detailed information on energy efficient envelope configurations.

An implementation of the NSGA-II genetic algorithm was written in Python language and made capable of exchanging information with the EnergyPlus building energy simulation tool. A population of N individuals was chosen to explore the search space for n generations. At each generation, a selection of the input variables was made by the genetic algorithm for each individual. The corresponding EnergyPlus input files were written and the energy simulations were subsequently launched. The output resulting from EnergyPlus was returned to the genetic algorithm in order to proceed to the next generation. At the end of the process, a set of Pareto front solutions – i.e. solutions that are equally optimal if all objectives in the problem are considered – was obtained. A case study was chosen to apply the proposed procedure.

2.1. Multi-objective search

Multi-objective search or optimisation differs from single objective in the fact that, in order to compare two solutions and determine which one is best (solutions A and B for example), their performance needs to be considered in multiple objectives and not just one. If objective functions are contrasting, it may not be the case that solution A outperforms B in *all* functions, it may be the case that A outperforms B in one function but B outperforms A in another. This relationship is studied with the concept of dominance, which can be summed up with the following statements:

- If solution A outperforms solution B in at least one function and outperforms or equals solution B in all the other functions, then solution A dominates solution B.
- If solution A outperforms solution B in one or more functions and at the same time solution B outperforms solution A in one or more functions, then solutions A and B do not dominate each other.

A non-dominated individual is one that is not dominated by any other individual in the population. A non-dominated individual typically dominates many the other individuals in the population and is never dominated by others. A non-dominated individual may have many individuals which he does not dominate, but none that dominates him.

The *Pareto front*, also called trade-off set or non-dominated set, is the set of all non-dominated solutions in a given group. They represent the set of solutions where one cannot be said to be better than another if all objective functions are considered in the problem.

2.1.1. Genetic algorithms

Genetic algorithms (GAs) are a family of search algorithms based on natural selection in the evolution of the species [40]. First proposed by John Holland in the mid 1970s in the University of Michigan [41], they have been successfully employed in many fields of study, including the architecture and construction field, and the energy efficiency of buildings and their components [7].

2.1.2. NSGA-II

NSGA stands for Non-dominated Sorting Genetic Algorithm. After a first non elitist Multi-Objective GA, NSGA-II was developed by Kalyanmoy Deb and his students in 2000 as an elitist version of NSGA [42]. Being a genetic algorithm, NSGA-II shares the same overall GA dynamic. There is a main loop that iterates generation by generation, there is fitness evaluation and there are selection, crossover and mutation operators. However, these operators are especially designed to work in multi-objective problems.

In comparison with the normal GA, NSGA-II has a series of modifications to its operators, most importantly its selection operator. NSGA-II does not directly use the fitness values to select the best individuals and, consequently, the individuals who will be used for reproduction. As its name suggests, NSGA-II uses a Non-dominated Sorting (NDS) algorithm to asses the position of all solutions in the objective space and to sort them according to Pareto fronts. Additionally, NSGA-II uses a special diversity preservation algorithm called Crowding Distance (CD). NSGA-II selects its best individuals according to a combination of the values obtained with the NDS and CD algorithms.

According to Attia et al., NSGA-II is the most efficient MOGA [7].

2.2. Energy simulation

Among the existing energy simulation tools, EnergyPlus was chosen to perform the evaluation of the building energy need. EnergyPlus is an energy simulation code with a modular structure developed by the US Department of Energy since 2001 [43]. The building thermal zone calculation method of EnergyPlus is a heat balance model [44], which is based on the following assumptions:

- the air in the thermal zone has a uniform temperature;
- the temperature of each surface is uniform;
- the surface irradiation is diffusive;
- the heat conduction through the surfaces is one-dimensional.

Neglecting the heat transfer due to infiltration and to inter-zone air mixing, the air heat balance can be written as:

$$C_z \frac{d\theta_z}{d\tau} = \sum_{i=1}^{N} \dot{Q}_{c,i} + \sum_{i=1}^{N_{surface}} h_i A_i(\theta_{si} - \theta_z) + \dot{m}_v c_p(\theta_e - \theta_z) + \dot{Q}_{sys}$$

where N is the number of convective internal loads, $\dot{Q}_{c,i}$, the term $h_i A_i(\theta_{si} - \theta_z)$ is the convective heat transfer from the ith surface at temperature θ_{si} of the zone to the zone air at temperature θ_z, whereas $m_v c_p(\theta_e - \theta_z)$ is the heat transfer due to ventilation with the outside air, and Q_{sys} is the system output. The capacitance, C_z, takes the contribution of the zone air into account, as well as that of the thermal masses assumed to be in equilibrium with the zone air.

3. Application to a case study

In the present work, an integrative approach for the early stages of building design is proposed to obtain detailed information on energy efficient envelope configurations by means of Multi-Objective Genetic Algorithms (MOGAs).

A multi-objective search was performed with the aim of minimising the energy need for heating, cooling and lighting of an open space office building by varying some envelope design variables. These variables were the thickness of the masonry walls, number, position and shape of the windows and the type of windows. The analyses were carried out both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo.

The search was performed through an implementation of the NSGA-II algorithm which was made capable of exchanging information with the EnergyPlus simulation tool.

3.1. Objective functions

The objective functions – or fitness functions – were the building energy needs for heating, cooling and lighting. These functions were minimised for a case study; the overall features of the analysed building are described in 3.2.

3.2. Description of the building

The case study was an open space office placed on the first floor of a five-storey masonry building. The internal size of the office was 20 × 14 × 4 m (width × depth × height).

As it will be further explained in 3.3, the optimisation was performed by allowing the GA to choose some design variables of the building envelope. These variables were the thickness of the masonry walls, the number, position and shape of windows and the type of windows. Details on the parametric model used to describe the geometry of the building are reported in 3.4.

The simulations were performed by locating the building in Palermo, Torino, Frankfurt and Oslo. These locations were chosen to investigate the outcomes of the optimisation in climates that, according to the Köppen classification, represent the vast majority of the European continent.

For each location, simulations were run both in a sub-urban and in an urban context. In the sub-urban configuration, the building did not have any surrounding building casting shadows on its façades. In the urban configuration, the building was surrounded by a grid of buildings having size 20 × 14 × 26 m and a distance of 14 m (Fig. 1).

3.3. Optimisation criteria

The optimisation was performed by changing the following parameters:

1. Thickness of the masonry walls. The thickness of the masonry layer of each façade was allowed to change freely in the range between 0.1 m and 1 m. The U-value of the walls was however kept constant. An external insulation layer was added to each wall and its thickness was changed accordingly to reach a fixed U-value of 0.33 W/(m^2 K). Modifications on the thickness of the masonry walls led to different values of internal heat capacity. Furthermore, the thickness of the walls influenced the reveal depth of the windows, hence modifying their shading.
2. Number, shape and placement of windows. The number, shape and placement of the windows in each façade were allowed to change freely. The windows were always positioned on the internal side of the wall. Since the insulation was placed on the external side of the wall, the resulting thermal bridge was supposed to be solved by turning up the insulation.
3. Glazing characteristics of the windows. The typology of window was chosen among eight options, whose glazing characteristics are reported in Table 3. The type of glazing was kept constant for all the windows of the building.

3.4. Parametric model

The parametric model used to describe the geometry of the problem was dependent on the maximum number of windows

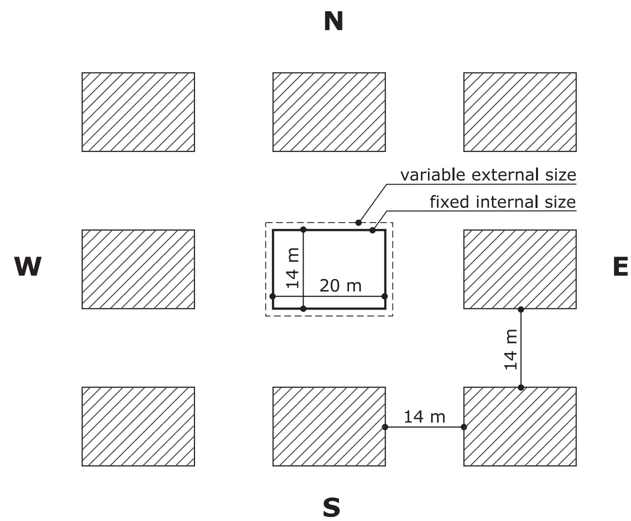


Fig. 1. Geometry of the urban context configuration.

that the GA could generate. To cover a large part of the solution space, more than one parametric model and search processes were needed. Fig. 2 shows the two parametric models used in this study. Model (a) described a single window which could cover at most the entire length and height of each façade. Model (b) described four windows distributed along the length of each façade. In this configuration, each window could cover at most 1/4 of the length of the façade and its full height. A border was however left to account for the presence of the side walls and floor slabs. In both models, placement and area of each window were determined by the position of two opposite vertices. Windows having any dimension smaller than 0.4 m were removed.

Along with the window configurations, the parametric model also changed the wall thickness in each façade. Thickness variation was used to modify the shading of the windows from the masonry overhangs and fins. An external EPS insulation layer was added to keep a constant U-value of 0.33 W/(m^2 K).

The parametric model selected the window type among those reported in Table 3 and used it for all of the windows in the building. The possible window constructions differed in the number of glass panes, presence and position of low-emissivity coating, thermal transmittance of the glazing, total solar energy transmittance and visible transmittance.

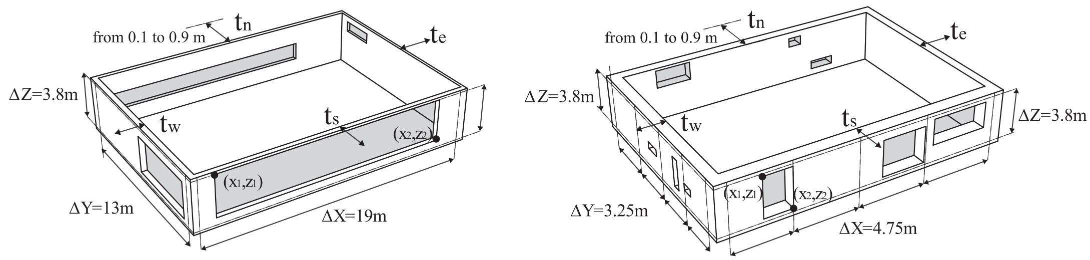
The number of variables in this case study is high. There is one window construction variable plus four variables for each window (x and y coordinates of two opposite vertices) and a variable for the thickness of each façade. This amounts for 21 variables for model (a) and 69 variables for model (b).

3.5. EnergyPlus model

The energy simulations were performed with EnergyPlus 8.0.0 [44].

Surfaces are modelled by EnergyPlus as planes. Since planes have no thickness, common practice is to use outside dimensions of walls to describe exterior surfaces and centreline dimensions to describe interior surfaces. However, to properly account for the heat capacity of walls, all surfaces were defined through their centreline dimensions [45]. The internal volume of the office room was kept constant and its value was specified as an input to EnergyPlus.

Windows were placed in their correct spatial position with respect to the centreline dimension of walls. Additional shading surfaces were modelled to account for the shading from the



(a) Parametric Model 1 Window (b) Parametric Model 4 Windows

Fig. 2. Parametric models: (a) model with one window per façade; (b) model with four windows per façade.

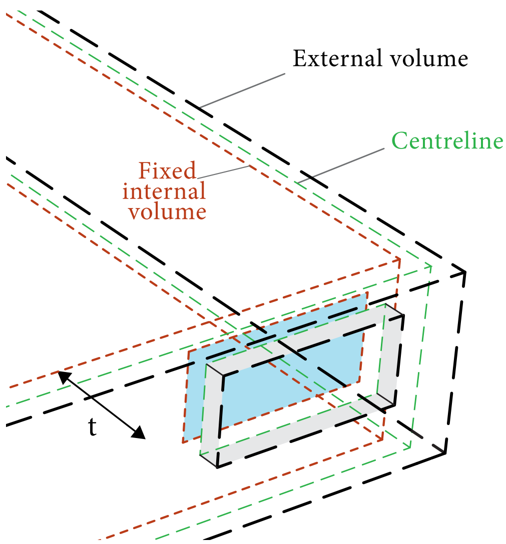


Fig. 3. EnergyPlus model.

external half of the walls (Fig. 3). Since the search aimed at investigating the self-shading deriving from the building itself due to the interaction between window shape and wall thickness, no other shading device was considered.

A fixed ground reflectance value of 0.15 was assumed [46].

Details on material properties and opaque constructions are respectively reported in Tables 1 and 2. The solar absorption coefficient of the external opaque surfaces was set to 0.6 (medium colour).

The glazing characteristics of the windows are reported in Table 3. For all the glazing solutions, the gaps were filled with 90% Argon. The U-value of the frame was fixed at 1.2 W/(m^2 K).

Internal gains deriving from people activity were set to 13.8 W/m^2 per zone floor area, whereas those deriving from electric equipment were set to 6.5 W/m^2. Occupancy and electric equipment schedules are reported in Fig. 4.

Daylighting control was performed with dimmed option. Two control points were placed along the longitudinal axis of the building and divided it into three equal segments. Illuminance set-point was set to 500 lx. For glare control, the occupants' seats were placed facing north. The maximum lighting level was set to 10 W/m^2 per zone floor area. The lighting schedule was set equal to the occupancy one.

Natural ventilation strategy was adopted. The ventilation rate was set to 1.7 air changes per hour during weekdays from 8.00 AM to 9.00 PM and to 0.25 h^{-1} during the rest of the day and during weekends [47].

The space was treated as a single thermal zone. Heating and cooling set point temperatures were respectively set to 20 °C and 26 °C from 7.00 AM to 9.00 PM during weekdays only.

The outcomes of the energy simulation process were building heating and cooling thermal energy need and electric energy consumption for artificial lighting.

Table 1
Characteristics of materials.

Material	t m	λ W/(m K)	ρ kg/m^3	c_p J/(kg K)
External gypsum	0.02	0.9	1800	840
EPS	Variable	0.031	112	1450
Bricks	Variable	0.5	1600	840
Internal gypsum	0.01	0.7	1400	840
Floor slab	0.25	0.678	1280	1000
Floor tiles	0.02	2.69	2700	984
Air gap	0.13	R:	0.18	m^2 K/W

Table 2
Constructions.

Component	Layer 1	Layer 2	Layer 3	Layer 4
Masonry wall	External gypsum	EPS	Bricks	Internal gypsum
Floor	Internal gypsum	Floor slab	Air gap	Floor tiles
Ceiling	Floor tiles	Air gap	Floor slab	Internal gypsum

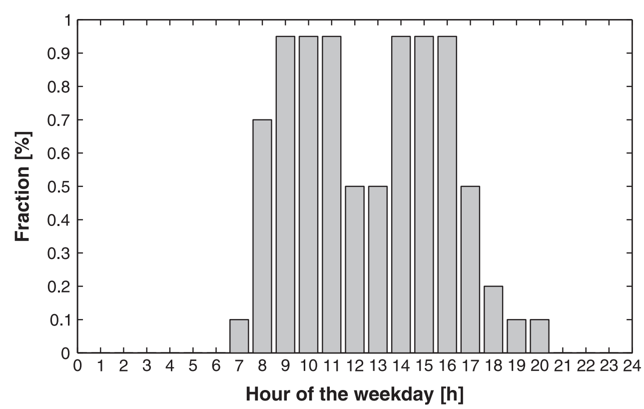


Fig. 4. Occupancy, lighting and electric equipment schedule.

3.6. GA inputs

The fitness functions for the present study can be explained by the following expression:

$$\text{Case Study}\begin{cases} \text{Minimise} & f_1(x) = Q_{H,nd} \\ \text{Minimise} & f_2(x) = Q_{C,nd} \\ \text{Minimise} & f_3(x) = E_L \\ \text{subject to} & 0 \leqslant x_{winPoints} \leqslant 1 \\ & 0.1 \leqslant x_{thickness} \leqslant 1 \\ & 0 \leqslant x_{winType} \leqslant 7 \end{cases}$$

Table 3
List of glazings.

Number	Composition	Position of low-e coating	U_g W/(m^2 K)	g –	τ_l –
0	4 \ 12 \ 4	–	2.68	0.77	0.81
1	4 \ 12 \ 4	3	1.31	0.60	0.80
2	4 \ 12 \ 4	3	1.31	0.64	0.82
3	4 \ 12 \ 4 \ 12 \ 4	3, 5	0.72	0.50	0.71
4	4 \ 12 \ 4 \ 12 \ 4	2, 5	0.74	0.55	0.71
5	4 \ 12 \ 4 \ 12 \ 4	3, 5	0.72	0.54	0.75
6	4 \ 12 \ 4	2	1.31	0.41	0.71
7	6 \ 16 \ 4	–	1.14	0.27	0.60

For all simulations, NSGA-II explored 100 generations with 50 individuals in each generation. The overall genetic inputs are reported in Table 4.

To investigate how distant the known Pareto fronts obtained with 100 generations of 50 individuals could be from the true Pareto front, a test run with 200 generations of 300 individuals was evaluated for the urban context study in Frankfurt. Since the outcomes were very similar, results obtained with 100 generations of 50 individuals were considered reliable.

4. Results and discussion

In the present work, the use of Multi-Objective Genetic Algorithms in the early stage of building design is proposed to obtain detailed information on energy efficient envelope configurations. An open space office building was selected as a case study. An implementation of the NSGA-II genetic algorithm was written and made capable of exchanging information with the EnergyPlus energy simulation tool. The optimisation aimed at minimising the energy need for heating, cooling and lighting of the building by varying some envelope design variables. These variables were number, position, shape and type of windows and the thickness of the masonry walls. The analyses were carried out both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo.

In Figs. 5, 6, 8 and 9 the objective spaces and Pareto fronts resulting from both configurations (sub-urban and urban context) are shown. The represented points are non-dominated solutions in the three-dimensional objective space obtained from both parametric models (one-window and four-window models). Individuals with a bigger marker are points that also belong to the bi-dimensional Pareto front relative to each represented projection of the objective space. Points A, B and C represent the best performers respectively for cooling, heating and lighting.

The analysis of the results considering solutions from both parametric models was performed regardless of the different exploration level they achieved.

4.1. Sub-urban context

In Figs. 5 and 6, the objective spaces and Pareto fronts resulting from the sub-urban context configuration are shown. A few relevant solutions from the Pareto fronts are presented in Fig. 7.

Table 4
Genetic inputs.

Population size (N)	50	
Number of variables	21 for model (a)	69 for model (b)
Number of binary digits	8 for win points	6 for thickness
Variable domains	$x_{winPoints} \in [0, 1]$	$x_{thickness} \in [0.1, 1]$
Mutation probability (p_m)	0.2	
End condition	End after 100 generations	

Even though heating, cooling and lighting energy needs greatly varied according to the climate, Pareto front shapes for all climates shared overall similarities. A high level of contrast between heating and cooling requirements, as well as between lighting and cooling requirements was observed in all locations. On the contrary, a very low level of contrast between heating and lighting was found. These results are not surprising, but a close examination of the front shapes reveals interesting and more specific information found in this study.

4.1.1. Cooling requirement

Solutions in the group of A's in Fig. 7 represent the best performing solutions for the cooling energy need in each location.

These solutions were similar to each other with the exception of Oslo. Solutions in Palermo, Torino and Frankfurt were characterised by a single wide and short window positioned in the upper part of the south-facing wall. The envelope presented very thick walls in all orientations, especially in the south-oriented façade. These wide and short windows resulted to be very well shaded due to the high thickness of the masonry overhangs. The absence of windows in the east and west orientations was useful to avoid solar heat gains.

It could be argued that the best solution would have no windows. However, the solutions without windows were outperformed by those with the short and wide south-facing window. The high position of the window on the wall could be justified by the need to ensure an effective natural lighting strategy. The lighting equipment represents a significant internal heat source. Since the energy model used a dimming control to reduce artificial lighting when unnecessary, the more daylight was available in the room, the less heat was introduced from the internal light sources. Therefore, it seems that if the south-facing window was well shaded while still introducing diffuse light, the cooling loads became lower.

Oslo's climate is characterised by very small cooling energy needs, hence the resulting solution in this fitness function is not very significant. However, results are interesting. The Oslo configuration had no window towards the south; it was characterised by a large and tall north-exposed window. This result could be explained by the fact that the sun-path during the summer months at Oslo's latitude is not as high as it is in the other climates. Lower sun-paths are harder to shade with overhangs, hence the GA opted to have no south-facing windows and to reduce lighting requirements by having a large north-facing window.

Another important aspect to discuss is the window type selected by the GA. Window type for Palermo was number 5, Torino and Frankfurt had window type 0 and Oslo had type 6 (see Table 3). Even though window type 0 was characterised by a high g-value, it also had a high visible transmittance. According to the aforementioned considerations on internal gains from light sources, if the windows are well shaded this selection makes sense. Types 5 and 6 had low solar energy transmittance values, hence they reduced solar gains.

Solutions in the group of A's were among the worst performing ones for heating and lighting needs since they tended to avoid solar radiation; they introduced just enough light to keep internal gains low.

4.1.2. Heating requirement

Solutions in the group of B's are the best performing solutions for the heating energy requirement.

Solutions in all locations were characterised by a very large and unshaded south-facing window whose area spanned the whole wall. The optimisation process selected these solutions to maximise solar gains during winter and hence reduce heating loads. Windows in other façades were very few and very small. The low solar gains

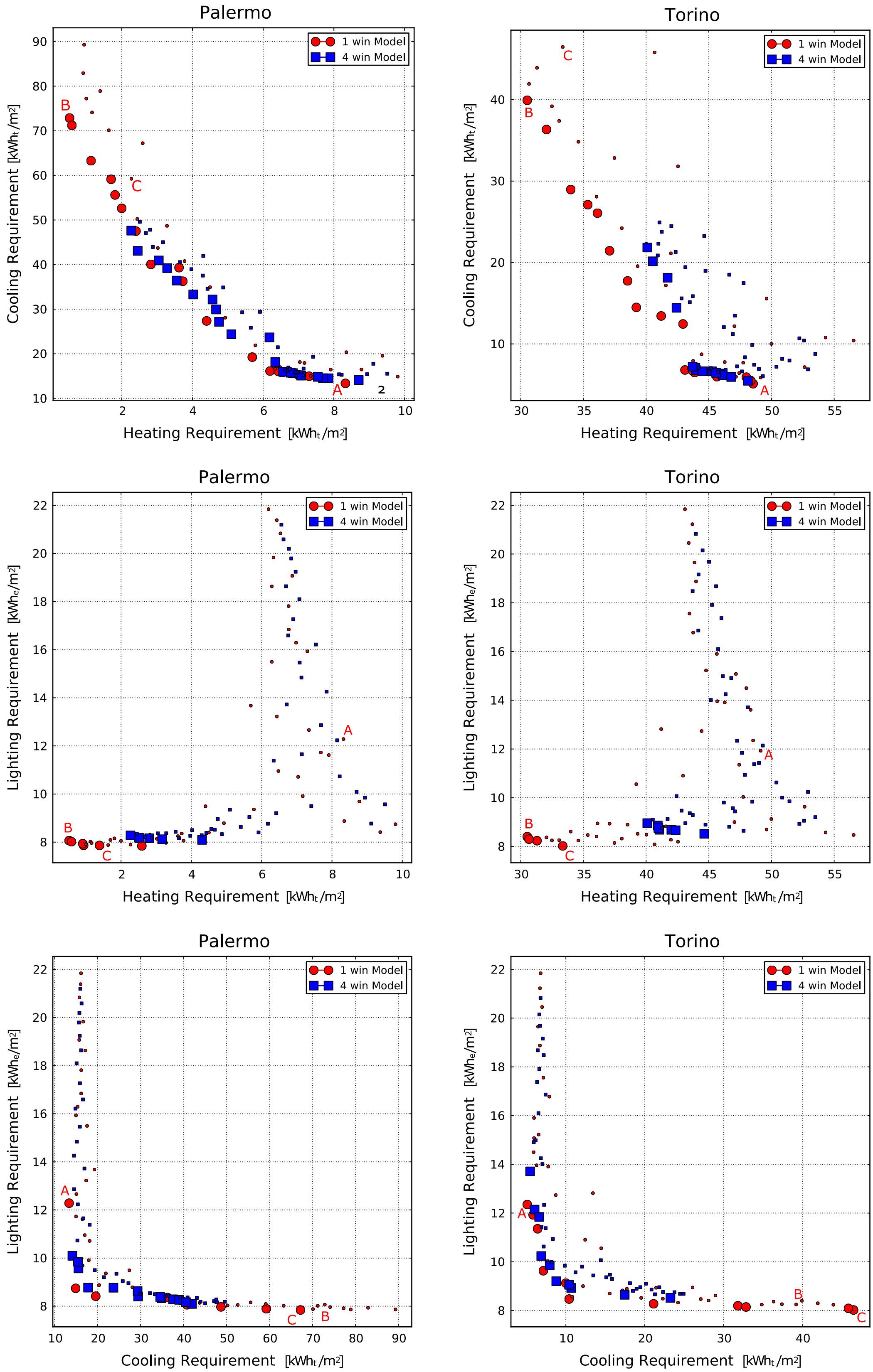


Fig. 5. Objective spaces for Palermo and Torino in presence of sub-urban context.

that can be available from east and west-facing windows during the winter months were not worth the loss of energy deriving from surfaces with a U-value higher than that of walls.

Window types selected by the GA for the winter months were characterised by a certain balance between low U-value of the glazing and high g-value and visible transmittance, especially

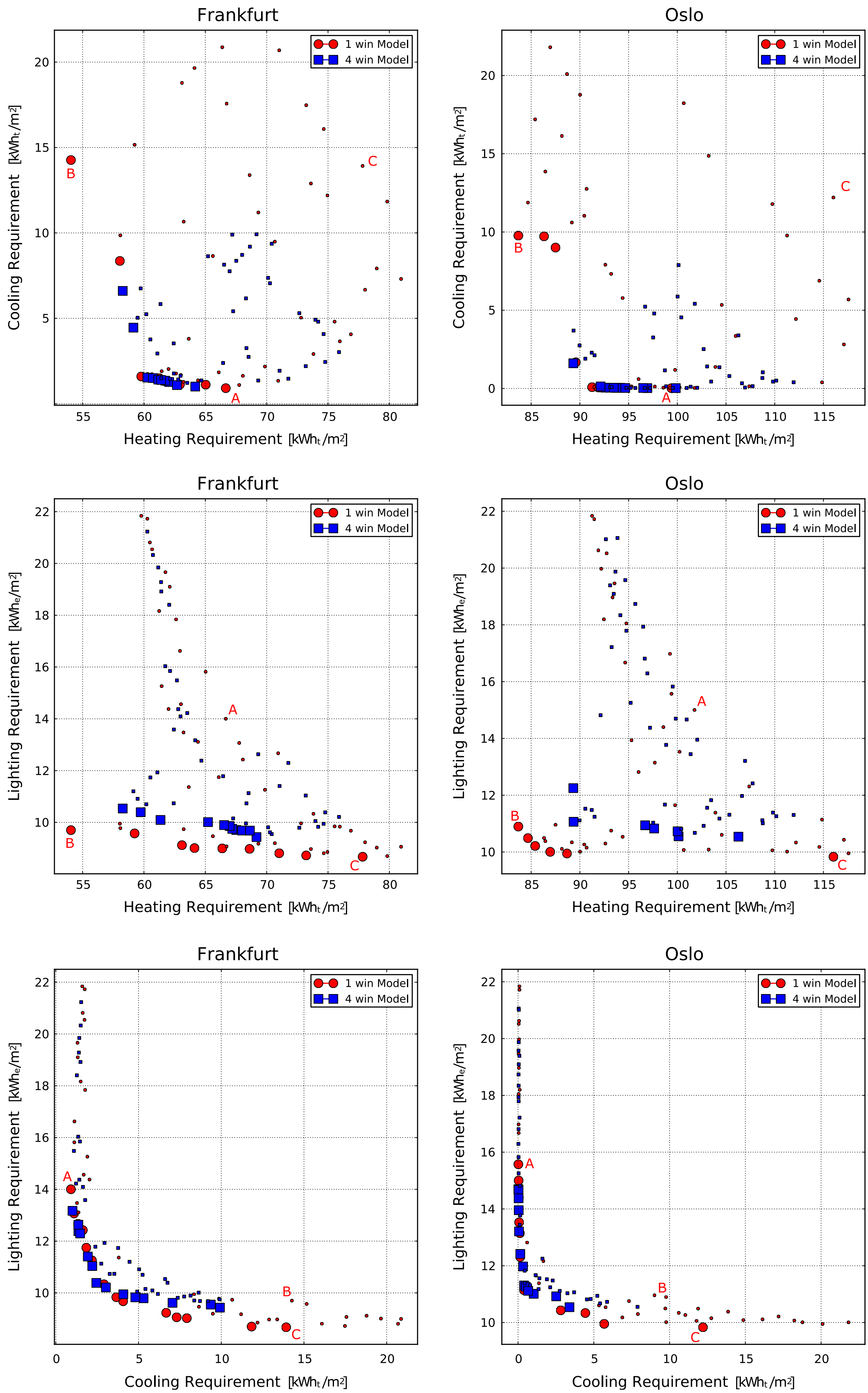


Fig. 6. Objective spaces for Frankfurt and Oslo in presence of sub-urban context.

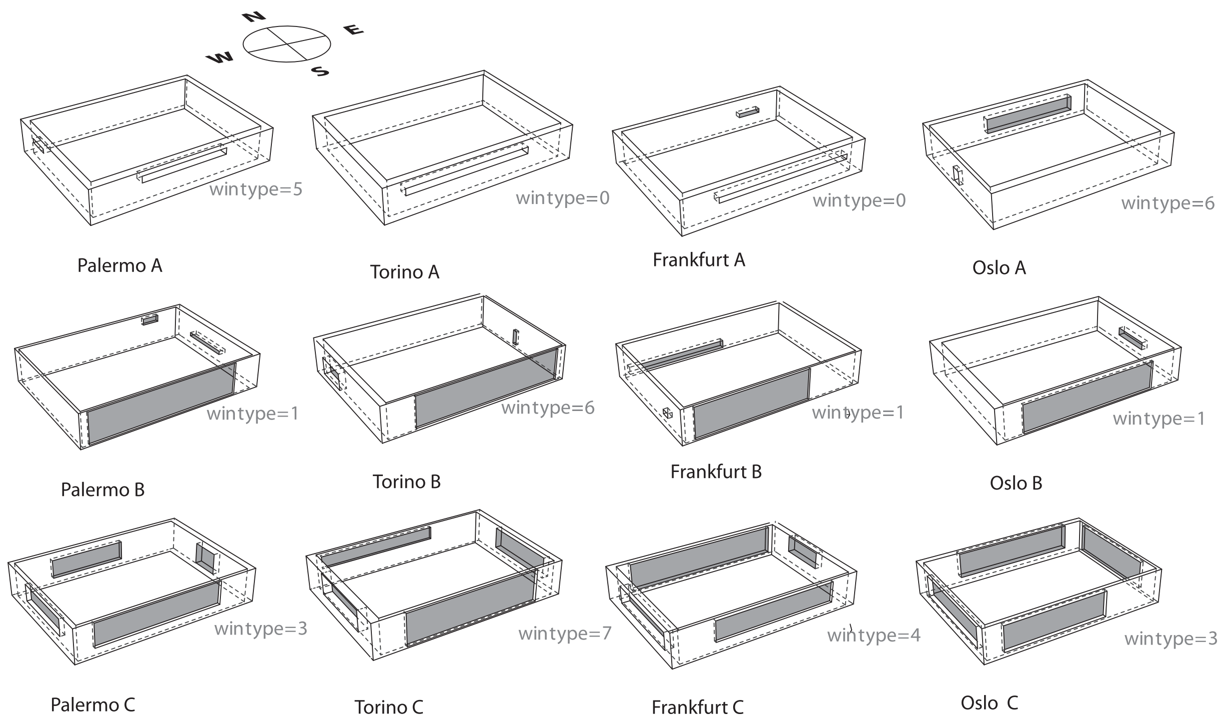


Fig. 7. Pareto front solutions for the configuration with sub-urban context.

type 1 which was selected for all the locations with the exception of Torino.

Another interesting result was the presence of thick walls in all the orientations with the exception of the south-facing walls. It can be inferred that south walls were kept thin to avoid shading, but other walls were much thicker. This is perhaps more evident in the Oslo B solution. The explanation for this finding can lie in the internal mass of the envelope.

Solutions in the group of B's were very poor performers in the cooling function, but they were among the best in the lighting function since they introduced a good amount of direct sunlight.

4.1.3. Lighting requirement

Solutions in the group of C's represent the best performing solutions for the lighting function.

Solutions in this category were characterised by large windows in all façades. Windows tended to be poorly shaded, especially in the north and south façades. Window types selected for this function (type 3, 4 and 7) were among the ones with the lowest U-values and solar energy transmittance. Even though the GA failed to find solutions with the highest WWR and visible transmittance, the best C solutions were characterised only by a slightly worse performance.

A low level of contrast would be expected between lighting and heating functions, and this seems to be true for the climates of Palermo and Torino. Heating energy needs between solutions in the group of B's and C's were only slightly different in these locations.

Frankfurt and Oslo showed a larger level of contrast between heating and lighting functions. Solutions in the group of B's and C's in these locations had indeed a very high difference in their heating needs. The reason for this was already suggested above, high window areas loose heat, and in cold climates they seem not to be worth it in north, east or west orientations.

4.2. Urban context

In this section, results obtained in presence of urban context are described. The objective spaces and Pareto fronts resulting from this configuration are shown in Figs. 8 and 9. Few relevant solutions from the Pareto fronts are presented in Fig. 10.

In general, window arrangements generated by the GA were characterised by significant differences in comparison with the solutions obtained for the sub-urban context.

The most evident result in presence of urban context regards the heating energy needs, which assumed higher values in comparison to the sub-urban context for all locations, whereas cooling needs were lower. The overall shapes of Pareto fronts were quite similar to those obtained with the sub-urban context, where a low level of contrast between heating and lighting was found. However, in presence of an urban context this behaviour was different; the degree of contrast between heating and lighting functions was very significant in Torino, Frankfurt and Oslo, and still present in Palermo. The reasons related to this trend will be further detailed in the analysis of the Pareto solutions. Furthermore, results suggest that, while having had less exploration during the GA run, the model with four windows had an advantage in this configuration.

4.2.1. Cooling requirement

For what concerns the cooling requirement, the best performing solutions in the study with urban context (solutions in the group of A's) shared some characteristics with those in absence of surrounding buildings. However, window areas were significantly higher.

As in the previous study, solution A for Palermo was characterised by a long and shaded window in the south-facing façade. However, in this case there was also a similar window in the north wall. Other high performing solutions for cooling had similar window arrangements. The window selected for this solution was type 3.

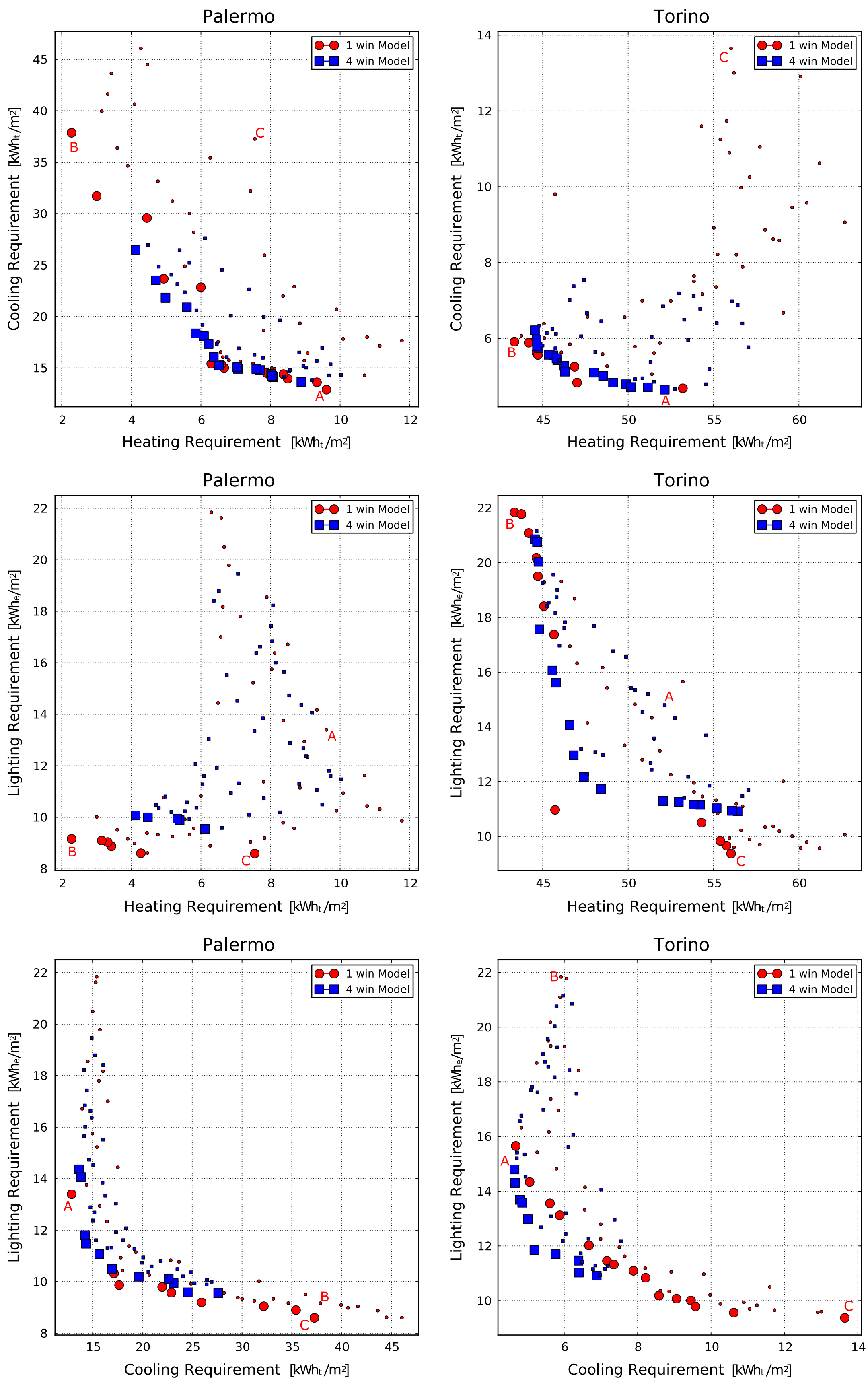


Fig. 8. Objective spaces for Palermo and Torino in presence of urban context.

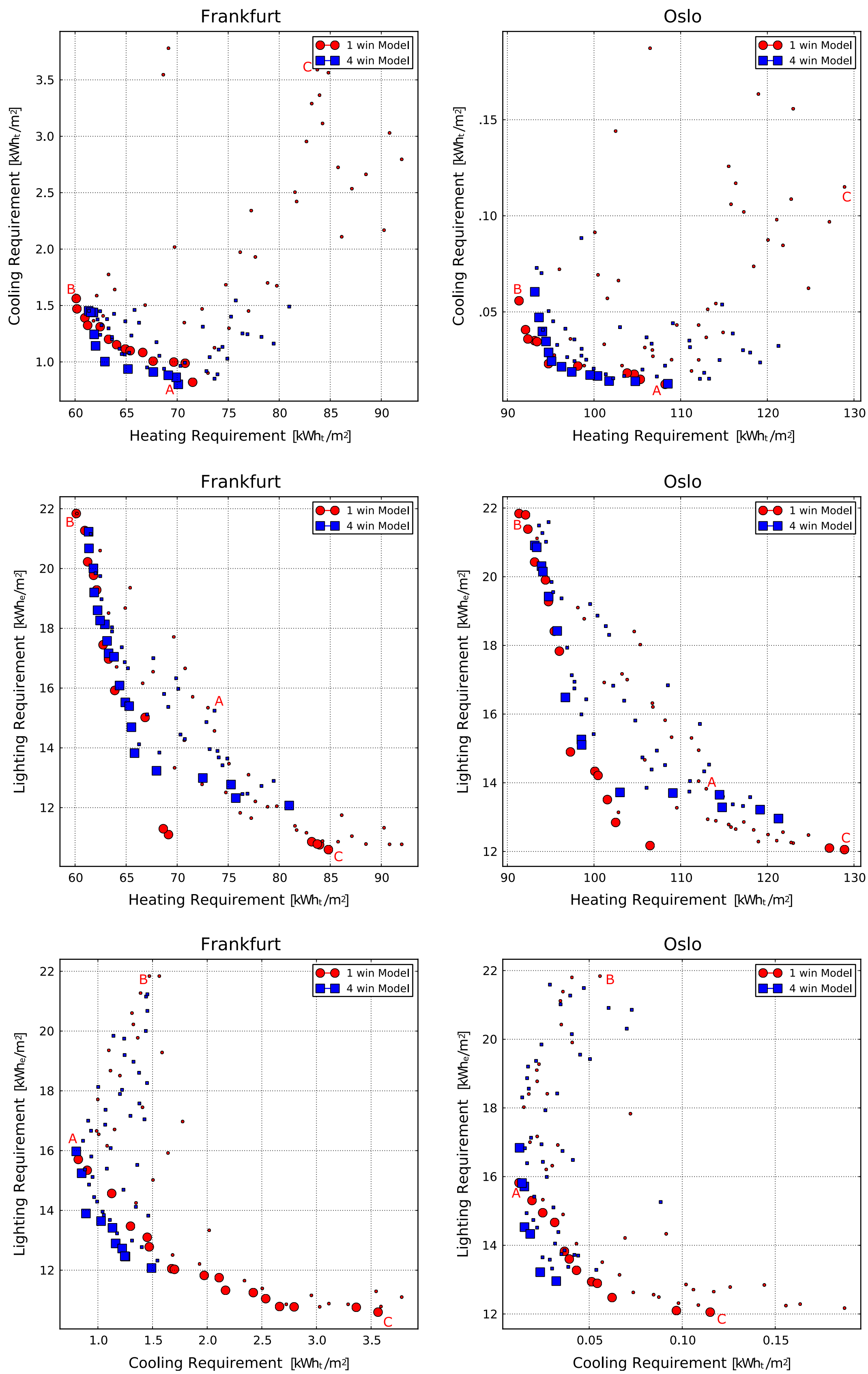


Fig. 9. Objective spaces for Frankfurt and Oslo in presence of urban context.

Solutions in the group of A's in Torino and Frankfurt had four mid-sized south-facing windows and some smaller ones in the other façades. Windows in the west and east façades were mostly vertical and walls were thick for them to be well shaded. The window selected for this solution in Torino was type 2, which was characterised by the highest visible transmittance, even though it

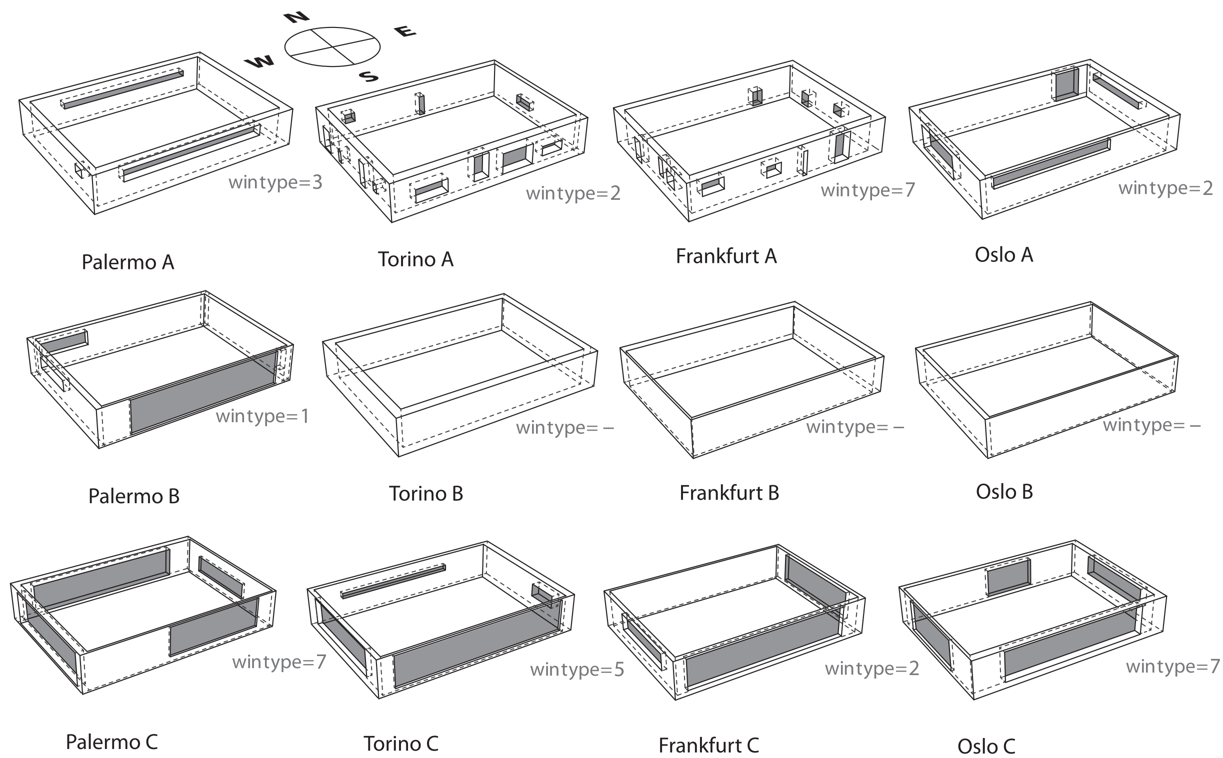


Fig. 10. Pareto front solutions for the configuration with urban context.

had almost the highest g-value. On the contrary, the window selected in Frankfurt was type 7, which was characterised by the lowest g-value, as well as the lowest visible transmittance.

Solution A in the Oslo climate had a long and shaded south-facing window, with additional windows in the other façades. Especially in the south and north façades, windows were placed asymmetrically in the walls. Also in this climate, the window selected for this solution was type 2, which could guarantee a high amount of daylight.

4.2.2. Heating requirement

In this configuration, heating requirements were significantly higher in comparison with those obtained with the sub-urban context; solar gains were much lower due to the presence of adjacent buildings. Since sun-paths in Palermo were still high enough during winter to allow for direct solar radiation into the office space, solution B in Palermo was quite similar to that obtained in absence of surrounding buildings. As in the sub-urban configuration, window type 1 was selected by the GA.

Solutions B in Torino, Frankfurt and Oslo were quite interesting results; no windows were present. In this configuration, the sun-paths in the Torino latitude and upwards were too low during winter for the windows not to be shaded by the adjacent buildings. Therefore, it can be inferred that the amount of solar gains provided by the windows did not counterbalance the heat losses due to their high U-values. In absence of windows, any variation in the thickness of the walls influenced only the thermal mass. However, it is important to remark that this result is affected by the position of the windows (they were on the first floor above the ground) in comparison with height and distance of the surrounding buildings.

With the exception of Palermo, solutions in the group of B's were obviously the worst performing for the lighting function. A good amount of contrast between heating and lighting functions could be consequently observed.

Even though solutions in the group of B's contained extreme examples that are clearly infeasible options for functional and aesthetic reasons, the fact that blind façades performed better than any other solution in Torino, Frankfurt and Oslo is a clear indication to designers; the introduction of any window would be made at the expense of heating energy requirement.

4.2.3. Lighting requirement

In every location, the best performing solutions for the lighting function were characterised by large windows in all the façades. Lighting energy needs did not increase significantly in presence of the urban context. Even though adjacent buildings decreased solar gains from direct solar radiation, daylight seemed not to be very affected. As in the previous configuration, the window types selected for this function (types 5 and 7) were among the ones with the lowest U-values and g-values. However, the window with the best visible transmittance (type 2) was selected for the Frankfurt solution.

5. Post-optimisation analysis

To perform an analysis of the Pareto front solutions for the investigated configurations, a statistical elaboration of the search space variables is presented in this section. A box plot representation was selected to investigate the statistical variation of the values assumed by the input variables in all the non-dominated solutions. The statistic analysis of the design variables within the Pareto sets was a fist attempt to understand the properties and the underlying structure of the optimal set itself. At a higher level, the post-Pareto analysis can be applied taking a wider knowledge on the actual meaning of the solutions into account. The introduction and the use of further knowledge at this stage would allow for a true expert post-Pareto analysis. At the decision maker level, the optimal Pareto solutions set would represent a pre-elaborated material, ready to be used for the development of the project.

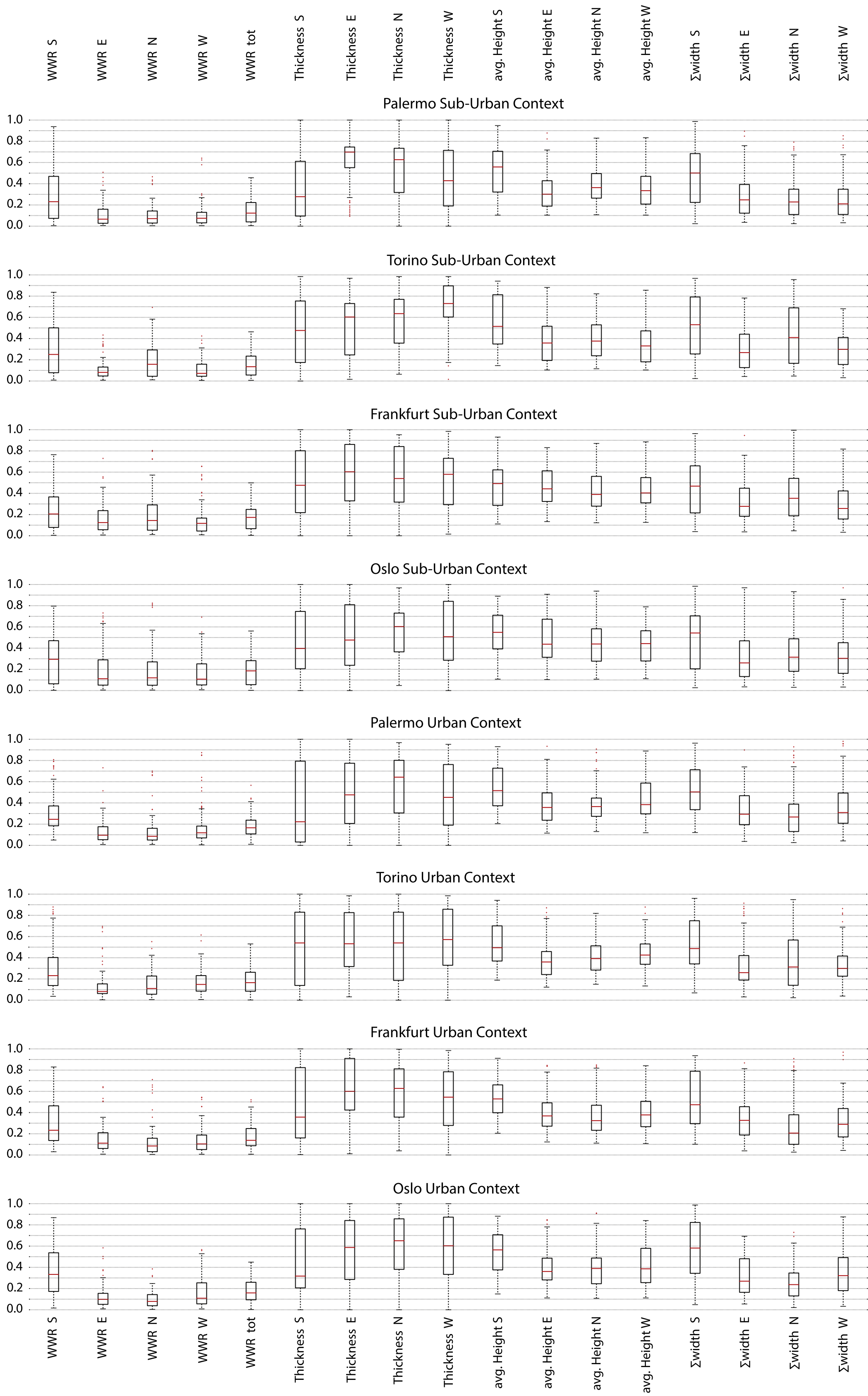


Fig. 11. Box plots of significant design variables for non-dominated solutions.

In descriptive statistics, box plots are a way for displaying the variation of datasets through their quartiles, without showing any information on the underlying statistical distribution. The spacing between the different parts of the plot indicate the degree of dispersion in the data. The boxes represent the interquartile range between the first and the third quartiles, whereas the lines within the boxes represent the median of the distributions. The lines that extend vertically from the boxes indicate variability outside the first (lower) and third (upper) quartiles up to the minimum and maximum values in the datasets, unless in presence of outliers, which are plotted as individual points. Outliers can provide important information on the dataset and may represent the key to the phenomenon under study.

The box plots related to the values assumed by a few significant input variables are shown in Fig. 11 for every location in both sub-urban and urban context. The selected variables are synthetic indicators which could be evaluated regardless of the number of windows in each façade. These variables are the Window-to-Wall Ratio related to each façade and to the whole building, the thickness of the masonry wall for each orientation, the average height of the windows in each façade and the total width of the windows for each orientation. All values were normalised within their range of variation. Only the solutions which globally accounted for all the non-dominated individuals deriving from both parametric models (one-window and four-window model) were considered in the analysis.

The aim of this analysis was to understand how the values of the design parameters spread within the Pareto front solutions set. In this way, information on the relative importance of the variables in the context of the optimal solutions and on the opportunity to reduce the number of design variables could be obtained. Variables characterised by a very low spread represent those inputs for which there is a low degree of freedom in the selection of their value. Since these variables should be almost constant for the solution to belong to the Pareto front, they could be disregarded as input variables in the optimisation process, obtaining in this way a faster convergence to the Pareto front. On the other hand, variables which have a great variability within the Pareto front solutions are those which may be the most important to optimise.

The outliers were often the extremal solutions that were discussed in Section 4.

Results of the box plots showed that, in optimal Pareto solutions, the variability of the WWR was wider on the south wall than on the other façades. In absence of urban context, optimal solutions were characterised by a WWR of the south walls spanning from about 0% to 80% and a median value of about 25%, whereas on the other walls the WWR range was narrower and the median was close to 10%. This means that the Pareto front solutions had either very small or no windows on the other façades. As previously stated, the range width is of interest for the optimisation process; a wide-span variable influences the results in a complex way, so that both low and high values can lead to optimal solutions. On the other hand, narrow ranges indicate that the correlation between variable and optimality is more direct.

In presence of urban context, for the climates of Palermo and Torino the spread of the WWR of the south façade decreased even though the median was practically not affected, whereas in the climates of Frankfurt and Oslo the median of the WWR of the south façade slightly increased but the spread was very similar to that of the sub-urban context.

In addition, in presence of urban context the total area of the windows tended to increase in Palermo and Torino, in Frankfurt remained almost unvaried while in Oslo decreased. From the analysis of the extreme solutions (Fig. 10), it could already be observed that opening a wider window area was not worthwhile in cold-dominated climates, for the higher heat losses through the windows would not be balanced by the low heat gains.

In absence of urban context, a slight increase of the total WWR could be observed as the latitude increased.

The higher the solar radiation reaching the building, the more the design choices for the south-exposed façade had a predominant impact on the energy need of the building. Moreover, the same effect could also be inferred considering the variation of solar radiation due to the presence of adjacent buildings.

Results of average height and total width of the windows were in agreement with the box plots of the WWR of the corresponding orientations. On the other hand, the box plots of wall thickness were much wider, indicating that the role of this parameter on the optimal solutions is not trivial.

It should be noted that the WWR-related results are specific to the building under investigation. The low WWR values found in this study are in accordance with previous researches which highlighted that the optimal WWR in walls with low U-values is smaller than in walls with higher U-values [25].

To retrieve additional information, further kinds of statistical analyses could be performed on the post-Pareto sets of solutions, taking also the distribution shape or the cross correlation between parameters into account.

6. Conclusions

The majority of decisions in the design process of a building are taken in the early design stage. Designers have to deal with multidisciplinary and contrasting objectives; energy efficiency, end cost and general performance of a building are strongly determined in this phase. Since the early design stage presents the greatest opportunity to obtain high performance buildings, it is necessary for designers to be able to gather pertinent building performance information.

In the present work, an integrative approach for the early stages of building design was proposed to obtain detailed information on energy efficient envelope configurations. By means of genetic algorithms, a multi-objective search was performed with the aim of minimising the energy need for heating, cooling and lighting of a case study.

The investigation was carried out for an open space office building by varying number, position, shape and type of windows and the thickness of the masonry walls. The search was performed through an implementation of the NSGA-II algorithm, which was made capable of exchanging information with the EnergyPlus energy simulation tool. The analyses were conducted both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo.

In addition, a simple analysis was performed by means of a box plot representation to investigate the statistical variation of the values that the input variables assumed in all the non-dominated solutions. Even though it was only a preliminary post-optimisation analysis on the Pareto fronts, this kind of investigation can potentially provide important information on the design variables for the early stage of the building design process. Variables characterised by a very low spread represent those inputs for which there is a low degree of freedom in the selection of their value.

Results confirmed the fundamental role that the window arrangements have in the energy efficiency and the importance of not disregarding the influence of the external environment.

Pareto front shapes for all climates shared overall similarities. In the sub-urban study, a high level of contrast between heating and cooling requirements, as well as between lighting and cooling requirements was observed in all locations. On the contrary, a very low level of contrast between heating and lighting was found. Results suggest that the optimisation process was particularly sensitive to internal gains due to artificial lighting.

In presence of urban context, the overall shapes of Pareto fronts were quite similar to those obtained with the sub-urban context.

However, the degree of contrast between heating and lighting functions was very significant in Torino, Frankfurt and Oslo, and still present in Palermo. A small glazed area was found to improve the fitness of the heating function. The low solar gains that can be available during the winter months in a heavily obstructed context did not counterbalance the heat losses due to the high U-values of the windows.

Results retrieved from the box plot elaborations highlighted a small Window-to-Wall Ratio of the building in all locations. Pareto front solutions were characterised by very low WWR values especially in east, west and north exposed façades. The area of the south facing windows was higher compared to the other orientations and characterised by a wider spread.

The outcomes of the search process can provide useful information for designers to make more conscious decisions. Among the whole non-dominated set of solutions, designers can decide which objective function they prefer according to the climate and to the adopted HVAC system. Furthermore, the choice can be also driven by more subjective and design specific information, such as visibility or aesthetics.

To directly account for architectural aspects, designers may use parametric models that have a minimum window area as a constraint. Windows may also be constrained in space, allowing the GA to move them only in certain areas where designers consider them to have the most visibility from the interior to the exterior or to have some aesthetic value.

Not all the aspects that are involved in the design of the building envelope were subject of study in this article. Future work will extend the energy performance optimisation to multidisciplinary search processes in order to include building structure and costs in the analysis. Furthermore, additional statistical elaborations of the non-dominated solutions will be performed to improve the usability of the outcomes of the optimisation and retrieve general information that can be useful for the early stage of the design process.

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